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NASA Technical Memorandum 107736

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(NASA-TM-107736) ATTENUATION OF EMPENNAGE BUFFET RESPONSE THROUGH ACTIVE CONTROL OF DAMPING USING PIEZOELECTRIC MATERIAL (NASA) 17 p

N93-23034

Unclas

G3/02 0157588

February 1993

National Aeronautics and
Space Administration

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SUMMARY

Buffet response results are presented from low-speed wind-tunnel tests of a simple, rigid model that was attached to spring supports. The two parallel leaf support springs provided a means for the model to respond in a vertical translation mode, thus simulating response in an elastic first bending mode. Wake-induced buffeting flow was created by placing an airfoil upstream of the model so that the wake of the airfoil impinged on the model. Model response was sensed by a strain gage mounted on one of the springs. The output signal from the strain gauge was feedback through a control law implemented on a desktop computer. The processed signals were used to "actuate" a piezoelectric bending actuator bonded to the other spring in such a way as to add damping as the model responded. The results of this "proof-of-concept" study show that the piezoelectric actuator was effective in attenuating the wake-induced buffet response over the range of parameters investigated.

INTRODUCTION[§]

Randomly varying pressures produced by such phenomena as separated flow, shock-wave boundary-layer interaction, and wake flows can produce significant buffeting structural response of airplane components. The internal structural loads resulting from these responses are important for two reasons. First, when added to loads from other sources, the resulting total load can approach limiting values. Second, the random nature of the loading can adversely affect the fatigue life of the structure.

Wake-flow-induced empennage buffeting, the subject of this paper, has been a significant area of concern for a number of years, beginning with the crash of the Junkers F13 commercial transport airplane at Meopham, England, in July 1930. This tragic accident, attributed to buffeting by British scientists[1] but blamed on other causes by an independent German investigation[2], precipitated a surge of empennage buffet research in Europe.[3-6] At the same time, independent studies in the United States had begun to focus on empennage buffeting.[7,8] During World War II many military airplanes of both U. S. and British design were affected by empennage buffeting.[9,10] Following the war, buffet studies while continuing to address the buffet problems of specific airplanes were expanded in attempts to gain a better understanding of buffeting and develop empirical means for predicting buffet responses and loads.[11-17] Currently, empennage buffeting is a significant area of concern for the teen-series fighter airplanes such as the F-15[18] and F-18[19,20], although most of the work has focused on the F-18. Even though a large proportion of recent empennage buffeting studies have addressed military airplanes, it can be a problem for commercial airplanes as well. This fact is evidenced by the tail damage due to buffeting that occurred for a DC-10.[21]

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§The references cited in the brief historical review presented in the second paragraph of the INTRODUCTION are only a small illustrative sample of the many works that are available in the open literature. A comprehensive historical review with complete bibliography was not intended.

Typically, undesirable buffet response of empennage surfaces has been treated by passive means--either adding structure to increase strength or extend fatigue life, or streamlining upstream components to reduce wake flows. An alternative approach would be to use an active control feedback system to attenuate the buffet response. Although active control methods have been evaluated extensively for flutter alleviation and other aeroelastic applications[22], such methods have been virtually ignored for buffeting, the work of Destuynder[23] that treated wing buffeting being a notable exception. Because recent active flutter suppression studies using piezoelectric actuators in feedback control systems have yielded some promising results for controlling wing and panel flutter[24-27], it appeared logical to evaluate this concept as a possible means to attenuate buffet response. Accordingly, a "proof of concept" study was initiated and the results therefrom are reported herein.

In particular, the purpose of this paper is to present buffeting response measurements made on a simple wind-tunnel model that was equipped with an active control feedback system that used a piezoelectric actuator. The tests were conducted in a small, laboratory-type, low-speed wind tunnel. The model was subjected to wake flow produced by an upstream airfoil. The wake produced by this airfoil buffeted the model in much the same way that the wake of the wing might buffet the empennage of an airplane. The model was attached to leaf springs that were configured such that the model was free to respond in a vertical translation degree of freedom thus simulating response in a first elastic bending mode. A strain gage mounted on one of the leaf springs was used to measure the dynamic response of the model. These response signals were fed back through a computer-implemented control law that supplied voltages to a piezoelectric actuator mounted on the other spring. Damping and dynamic response data are presented for three cases--open loop (control system off) and two values of feedback gain.

PIEZOELECTRIC CHARACTERISTICS

Piezoelectric materials generate a mechanical strain when subjected to an applied voltage, or conversely generate a voltage when they are mechanically strained. Certain manmade materials may be made piezoelectric by applying a relative large voltage across a sample of the material. The applied voltage causes the dipoles within the material to become realigned in an orderly fashion such that the positively charged ends of the dipoles are oriented towards the negative pole of the applied voltage. If the voltage is applied for a sufficient length of time, the dipoles retain their orientation when the voltage is removed. The sample is now said to be poled. Subsequent applications of smaller voltages to the sample will cause the dipoles to reorient themselves, positive ends of dipoles attracted to negative pole of applied voltage thus causing the specimen to deform. When this smaller voltage is removed, the dipoles return to their poled alignment and the sample returns to its undeformed shape. This electromechanical coupling is illustrated by the sketch in figure 1 which shows a sample of material that was originally poled in the z direction. If a voltage difference is applied in the z direction but in the opposite sense from the original poling voltage, the specimen will, as shown in the figure, thicken and shorten (a Poisson-like effect) in the two in-plane x and y directions If the applied voltage is in the same sense as the poling voltage, opposite effects take place.

By attaching small pieces of piezoelectric material to an elastic structure it is possible to create actuators which can be used to deform the structure. By controlling the voltages applied to the piezoelectric patches the structure can be made to deform in a desired manner. A bending actuator (commonly referred to as a bimorph configuration) is illustrated in figure 2. The sketch at the top of the figure illustrates a beam to which a piece of poled piezoelectric material has been bonded to each side. The arrows indicate the direction of the original poling voltage. If excitation voltages are applied to the patches as shown in the bottom sketch, the top patch will expand whereas the bottom patch will contract, thus causing the beam to bend. By controlling the magnitude and sense of the excitation voltages supplied to the actuator the beam can be bent in a prescribed fashion. For the present study a bending actuator made of lead zirconate titanate (PZT), a piezoceramic, was used. Details of this actuator and its mounting are discussed later.

An excellent review and extensive bibliography of the use of piezoelectric actuators and other "smart structure" concepts is given in reference 29.

MODEL

The wind-tunnel model was a modified version of the one used by Heeg[25] in a previous study using piezoelectric actuators for active flutter suppression. A photograph of the model system is presented in figure 3. The rectangular-planform wing had a 4-inch span and 4.5-inch chord. The airfoil section was a 5-percent-thick double wedge with the point of maximum thickness at the one-quarter chord. The wing was constructed of an aluminum alloy plate that was covered with balsa wood. Mass balance was provided by aluminum alloy tape. The wing panel was very stiff, rigid in the content of the present study.

As shown in the figure, the wing was attached to a pair of parallel leaf springs mounted outside of the flow. Each steel spring was 0.016 inches thick, 1.25 inches wide, and 6.0 inches long. The springs were clamped at both ends. One end of each spring was clamped to a support strut that was tied to the plastic plate that formed the ceiling of the wind-tunnel test section. The other ends were clamped to a medal block that was in turn attached to a very stiff rod that passed through a slot in the ceiling plate and attached to the model. This mounting arrangement provided for a vertical translation degree of freedom with a natural frequency of about 8.9 Hz.

A four-active-arm resistance wire strain gage bridge was mounted near the root of one of the leaf springs. The output signal of the gauge was proportional to the vertical displacement of the model.

A piezoelectric bending actuator was installed near the root on the spring without the strain gage. A 1.5-inch-long by 1.00-inch-wide by 0.0075-inch-thick PZT plate was bonded to each side of the spring. The actuator can be seen in the figure 3 photograph. A sketch of the installation is shown in figure 4. The plates were bonded to the spring with like poles oriented toward the spring. The 0.005-inch-thick bonding layer electrically insulated the piezoelectric plates from the steel spring. Small copper tabs were attached to the plates during the bonding process to provide a mean of applying voltages to the bonded side of each piezoelectric plate. Additional insulation was applied to the exposed portions of the copper tabs to insulate them from the plate.

WIND TUNNEL

The experiments were conducted in the Langley Flutter Research Experimental Device (FRED) which is a small, low-speed, laboratory-type, open-return wind tunnel. A photograph of the FRED is presented in figure 5. A sketch of FRED is presented in figure 6 as are some of its characteristics. The wind tunnel is powered by a two horsepower, variable speed electric motor connected to a squirrel cage fan located downstream of the 6-inch-square test section. Honeycomb screening at the beginning of the entrance cone is used to ensure smooth flow in the test section. The tunnel speed is continuously controllable up to a speed of about 74 knots. The walls and ceiling in the test section are made of clear plastic so that the model may be easily observed. Models are usually mounted from the ceiling as was the case for this study.

For the present study FRED was modified so that a rigid airfoil could be placed at the upstream end of the test section. A schematic representation of this setup is presented in figure 7. The wake from this airfoil was used to generate buffeting flow. The angle of attack and position of this airfoil could be easily adjusted so that the resulting wake would impinge on the model mounted downstream. The angle of attack and airfoil position selected for the present test was obtained by trial and error. The configuration finally selected was the one that produced the largest buffet response of the model. Once the final position of the airfoil was selected, the wake-generating airfoil was clamped into place. Therefore, all of the buffet response data presented herein were obtained for the airfoil in the same location and orientation. Although no quantitative measurements were made of the characteristics of the wake flows, some qualitative measurements were made using a pressure probe to ensure there were not any unusual peaks in the spectrum of the wake in the frequency range of interest. None were found.

FEEDBACK SYSTEM

A block diagram of the feedback system is presented in figure 8. The output analog signal from the strain gage bridge mounted on one of the support springs was amplified and routed to an analog-to-digital converter which had a sample rate of $1/\tau$. The strain gage signal is proportional to and in phase with the displacement of the model. The digitized signal was then sent to the control law which was implemented on a desktop personal computer. The control law was a simple gain system. That is, the digital signal was only multiplied by a constant value -K. The gained signal was next routed to a one step time delay $e^{-\tau s}$ where s is the Laplace operator and τ the time between samples as indicated above. The time delay provides a means for changing the phase of the feedback signal. The gained- and phased-shifted signal was converted back to an analog signal by a zero-order-hold digital-to-analog converter. The transfer function of this converter is $(1 - e^{-\tau s})/s$. The converted signal was routed to an operational amplifier. The output signal from this amplifier was used to drive the piezoelectric actuators. The maximum output voltage of this amplifier was +/- 80 volts.

For the present study a sampling rate of 400 samples per second was used. This relatively high rate was chosen to ensure that the buffeting wave form was well defined. The transfer function amplitude and phase that results from this rate are presented in figure 9 as a function of the ratio of frequency to frequency of the vertical translation mode, f/f_{trans}. The magnitude of the transfer function is almost constant over the range of f/f_{trans} shown in the figure. The phase angle gradually decreases from a value of 180° at zero frequency as f/f_{trans} increases. The phase shift at the frequency of the translation mode, $f/f_{trans}=1.0$, is about 168∞. Had a lower sampling rate been used, the phase angle at $f/f_{trans}=1.0$ would have been smaller. The closer the phase angle to 90° the more effective the feedback system should be in introducing damping into the system.

Two values of the gain -K were used, namely, 14 and 29. The 29 gain was the value that caused the system to begin to saturate at a tunnel velocity of about 39 knots. The 14 gain was the value that caused saturation to begin at a velocity of about 74 knots.

The feedback system was implemented on a personal computer with a 80386 processor and a 80387 co-processor running under a real time operating system. The computer was programmed in C-language. All calculations were made using floating point arithmetic. The analog-to-digital converts were 12 bit units. This implementation was similar to that used by Dunn [29] in a previous study of vibration suppression of large structures.

TEST PROCEDURE

With the control law gain set to the desired value the tunnel speed was increased to and then held constant at a preselected value. Damping and buffet response measurements were made at velocities of 9.7, 19.4, 29.2, 38.9, and 48.6 knots. Damping data were also obtained at a velocity of 4.4 knots. (Because the present study was conducted at nominal sea level altitude and the speeds were very low, the test section density was essentially the sea level value. Consequently, the true velocity is essentially equal to equivalent airspeed.) The output signal from the strain gage bridge was routed to a transfer function analyzer that was used to calculate the autocorrelation function of the response signal. The final autocorrelation function was an ensemble average of many individual measurements. The root-mean-square value of the response was obtained by taking the square root off the value of the function at time zero. The damping of the response was obtained from the log decrement of the function. A typical autocorrelation function is presented in figure 10. Autospectra of the responses were also obtained to ensure that there was no model response in spurious modes. These spectra showed that the model responded only in the vertical translation mode. The quality of the autocorrelation functions as indicated by the typical one shown in figure 10 supports this fact as well.

RESULTS AND DISCUSSION

Total damping and dynamic response data were acquired over a range of speeds for open loop (control system off), and two values of control system gain, namely, 14 and 29. The results of these measurements are presented and discussed in this section. The data are presented as their respective variations with velocity measured in knots. As discussed previously, the damping and response data were obtained from autocorrelation functions of the model response. The frequency of vertical translation mode remained essentially constant at 8.9 Hz over the range of parameters covered in this study.

Damping

Variations of the damping ratio $g = 2\ C/C_{cr}$ with airspeed V in knots are presented in figure 11. The values of damping at zero velocity for the open-loop case correspond to the structural damping ratio. The use of the feedback system increased the structural damping ratio substantially--the higher the gain, the larger the damping. For the open-loop case, circle symbols, the damping increases with increasing velocity. This trend is essentially linear. The curve faired through the data points is a linear least square fit. The increase in damping that occurs with increasing velocity is due to aerodynamic effects. So, for the open-loop case, the difference between the total damping at a given velocity and the structural damping at zero velocity is the aerodynamic damping ratio. The closed-loop gain=14 data also show a linear increase in total damping with velocity. Again, the curve faired through the data is a linear least square fit. There is more scatter in these data than there was for the open-loop data. The difference between the gain=14 data and the open-loop data at the same velocity is the damping increase produced by the feedback system. This increase is constant over the range of velocities studied because the curves through the open-loop and gain=14 data are parallel. The closed-loop gain=29 data, triangle symbols, show a further increase in damping. The curve fared though these data is also a linear least square fit. The relative performance of the feedback system deteriorates with increasing velocity. For example, the damping added by the control system at V=29 knots is less than the damping added at 10 knots.

Although for gain=29 the control system began to saturate at about V=39 knots, it was still possible to estimate the damping for this and the higher test velocity, about 49 knots, from the autocorrelation functions. These values are indicated in the figure by the solid triangle symbols. As would be expected, control system performance was adversely affected once saturation began to occur. Note that the estimate of the total damping for the gain=29 case at V=49 knots is lower than it is for the open-loop case.

The effectiveness of the active control system in increasing the damping can be seen by comparing the three autocorrelation functions presented in figure 11 for V=19.4 knots. A visual inspection of there functions clearly shows the increase in damping that occurs as control system gain is increased. Furthermore, it is easily seen that the response frequency is essentially the same for the three cases.

Response

Variations of the root-mean-square response σ with flow velocity are presented in figure 13. The open-loop data, circle symbols, show an increase in response with increasing velocity. Although the trend appears at first glance to be linear, close examination shows that there is a small amount of nonlinearity present. The curve through the data is a second degree least square fit which fares through the individual data points quite nicely. The closed-loop gain=14 data, square symbols, indicate a similar trend but with a lower response. Again, the faired curve is a second degree least square fit. A similar trend was found for the closed-loop gain=29 data, triangle symbols, with these responses being the lowest of the three cases. A second degree least square fit was also used to fair the curve though these data points. The two solid triangle symbols represent gain=29 data for the two test velocities where some saturation of the feedback system had occurred. As would be expected, saturation adversely affected control system performance. Indeed, the response at the highest velocity, about 49 knots, is higher than for the open-loop case. This is consistent with the damping estimates at this velocity which were lower than the open-loop case.

CONCLUDING REMARKS

Data have been presented from using a piezoelectric actuator in a feedback control system to attenuate the buffet response in low-speed, wind-tunnel tests of a relatively simple model that was free to response in a vertical translation degree of freedom. The vertical translation degree of freedom was provided by two parallel leaf springs. The wake of an upstream-mounted airfoil was used to produce wake-induced buffeting response as might be experienced by an airplane empennage. Model response was measured by a strain gage mounted on one support spring. These signals were feedback through a control law implemented on a desktop computer. The resultant output command signals were routed to a piezoelectric bending actuator mounted to the other support spring. Data were acquired for open-loop and two closed-loop conditions. Over the range of parameters covered, the control system was effective in increasing the damping of the translation mode and attenuating the buffeting response--the higher gain the larger the damping and the smaller the response.

It should be pointed out that this relatively simple study was in the nature of a "proof of concept." It should not be inferred that piezoelectric materials are ready for use in a full-scale airplane application. Such applications will depend on many factors which were not investigated in this study, and many factors which are still unknown. What should be inferred, however, is that piezoelectric materials have the potential for use as "buffet suppressers," but considerably more research and development work is needed before this potential can be realized.

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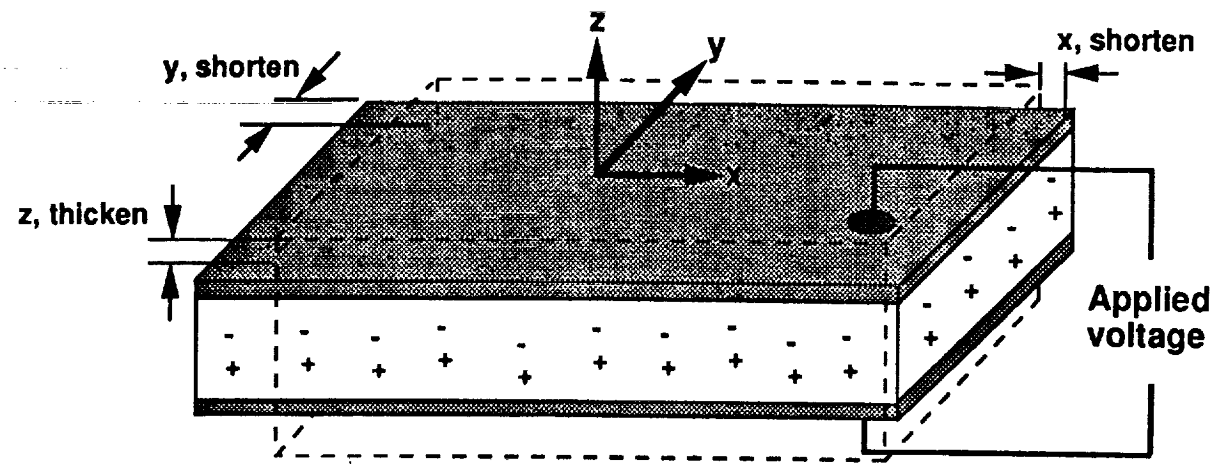

Figure 1. - Piezoelectric characteristics.

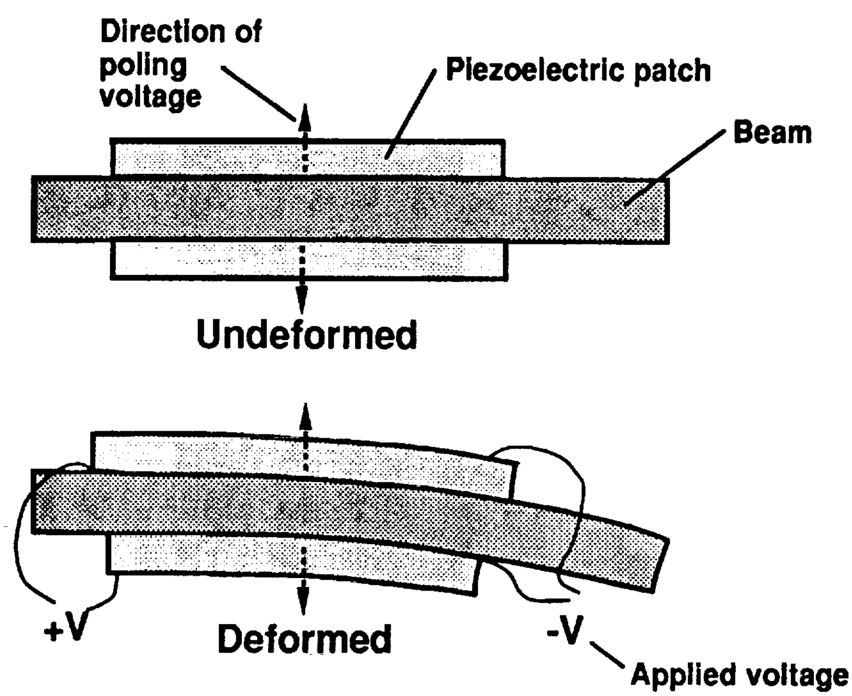

Figure 2. - Piezoelectric bending actuator.

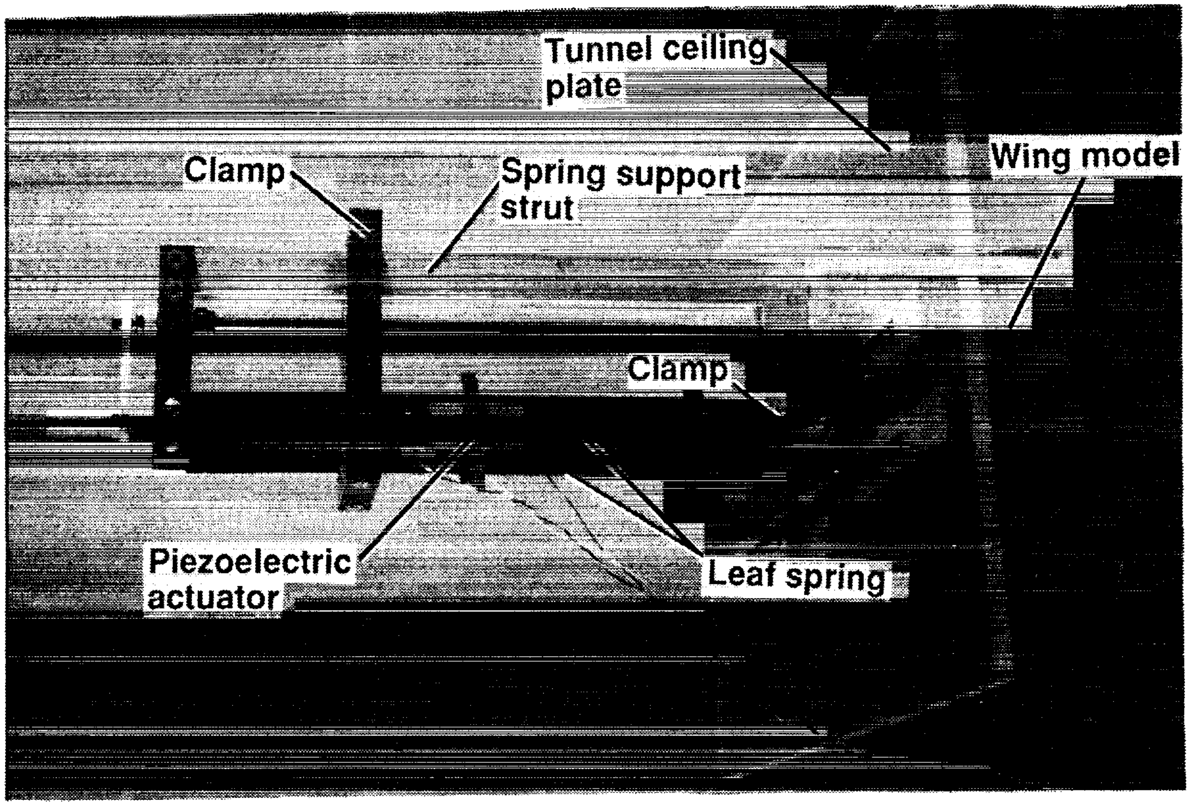

Figure 3. - Wind-tunnel model and support system.

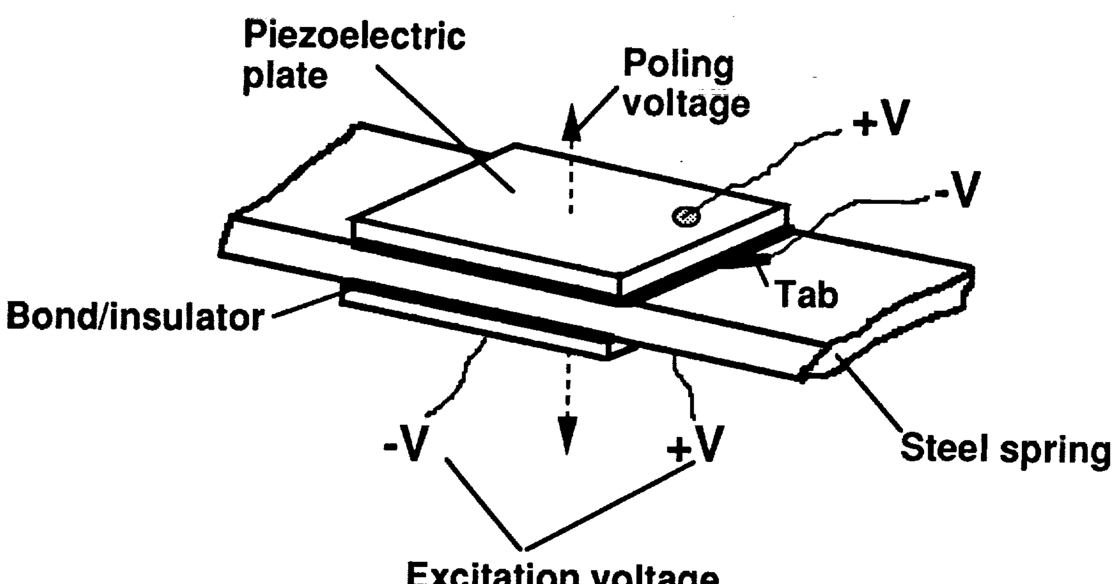

Figure 4. - Installation of PZT piezoelectric bending actuator.

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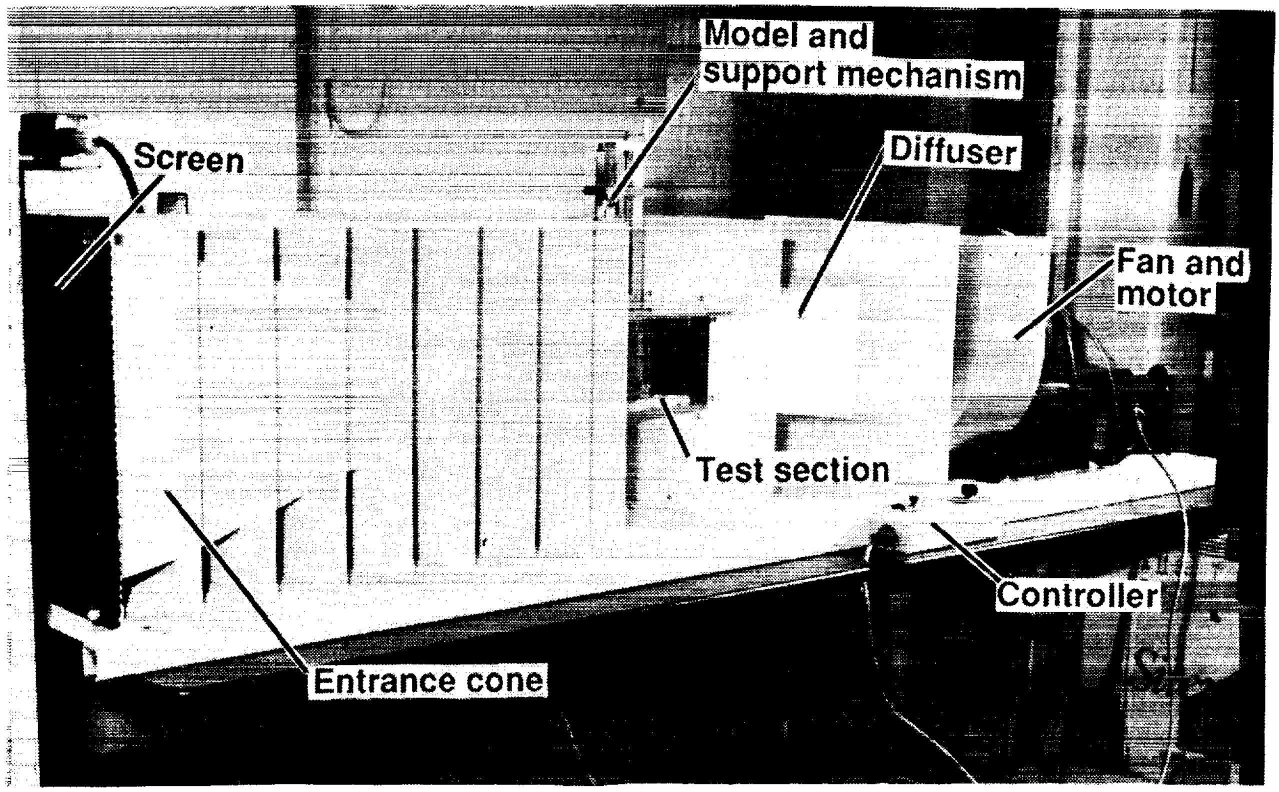
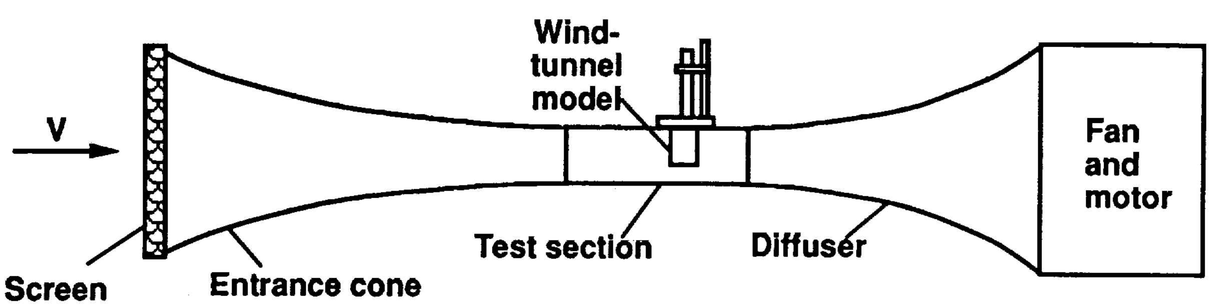


Figure 5. - Flutter Research Experimental Device (FRED).



Type: Low speed, open return

Power: 2hp electric motor

Pressure: Atmospheric

Speed: 125 ft/sec, 74 knots

Test section: 6-inch-square

Model mounting: ceiling

Figure 6. - Sketch of Flutter Research Experimental Device (FRED).

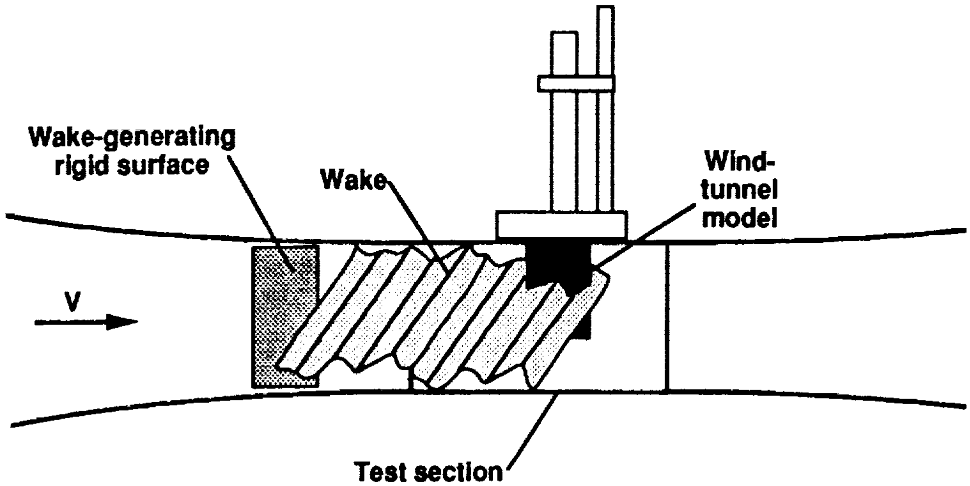


Figure 7. - Wake generator.

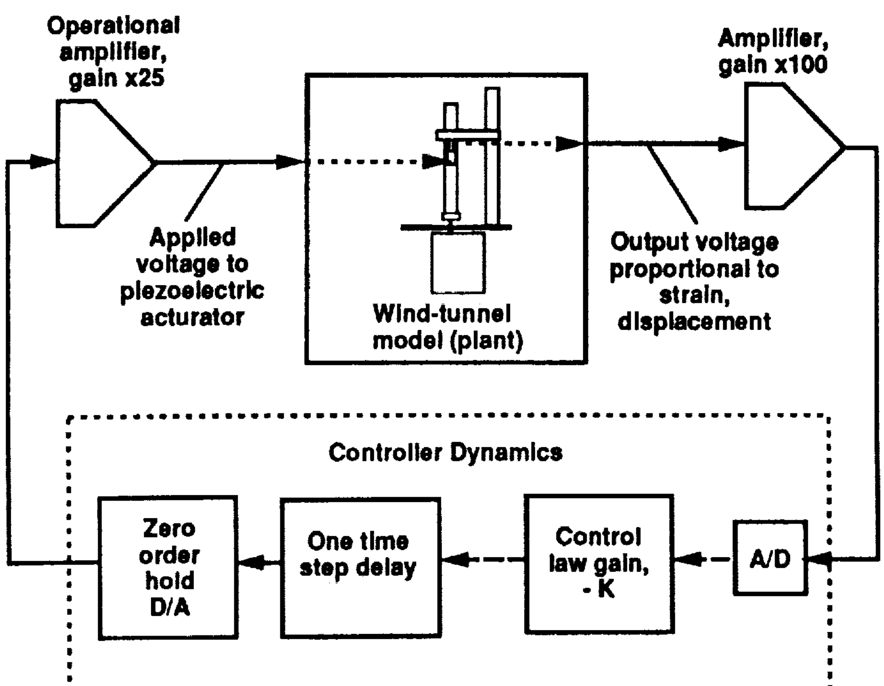


Figure 8. - Block diagram of feedback system.

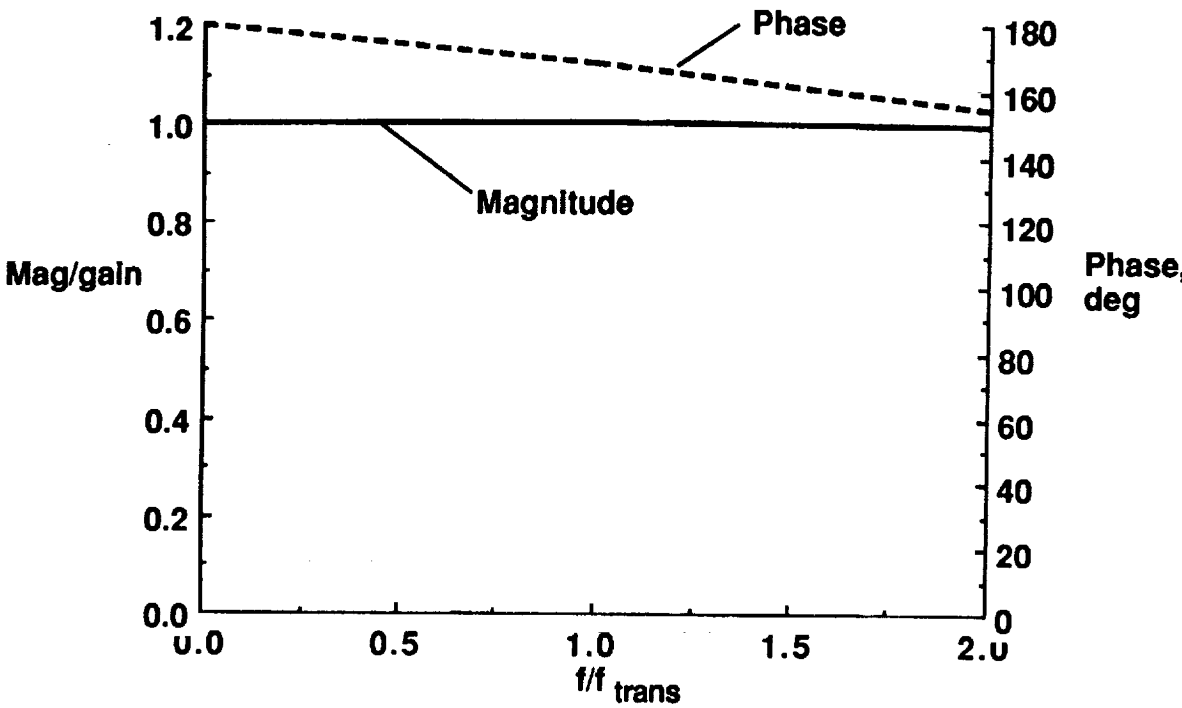


Figure 9.- Transfer function.

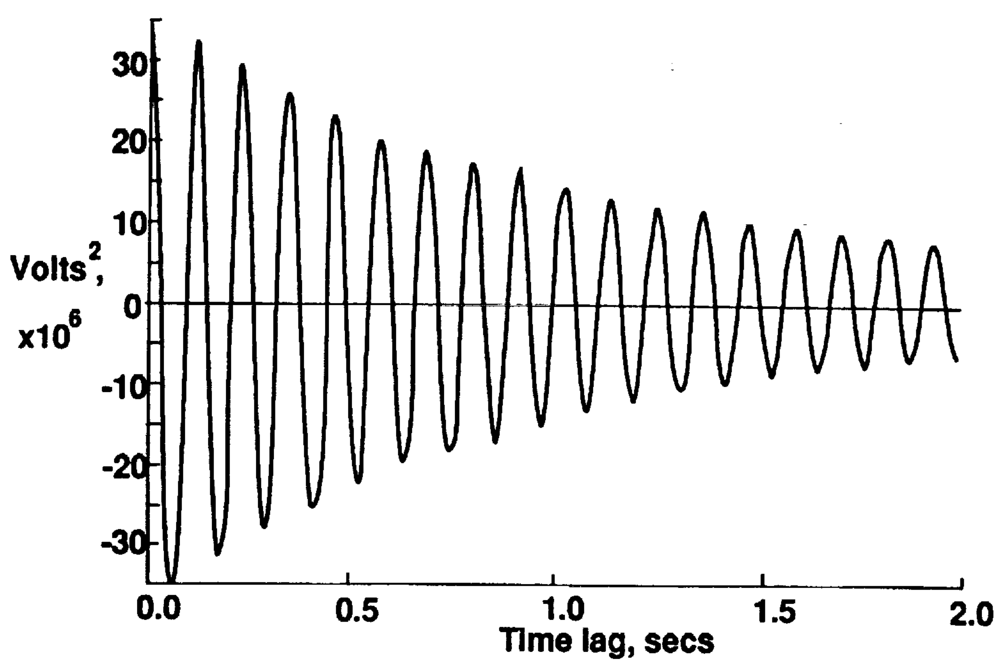


Figure 10. - Typical autocorrelation function.

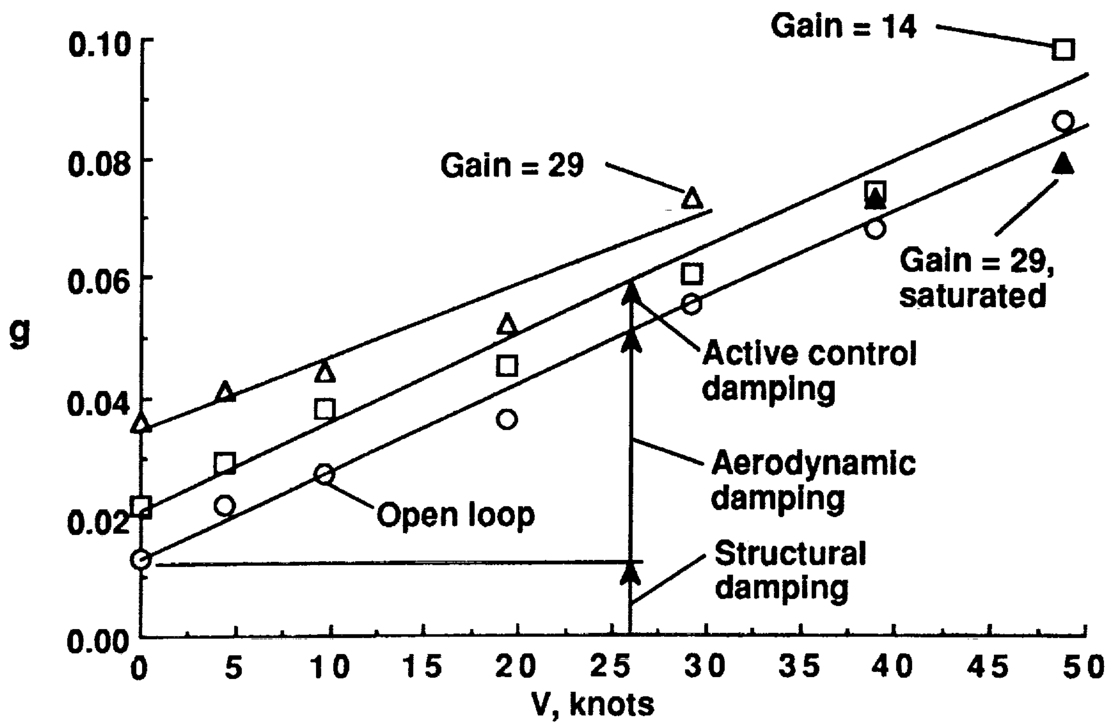


Figure 11. - Variation of damping with velocity.

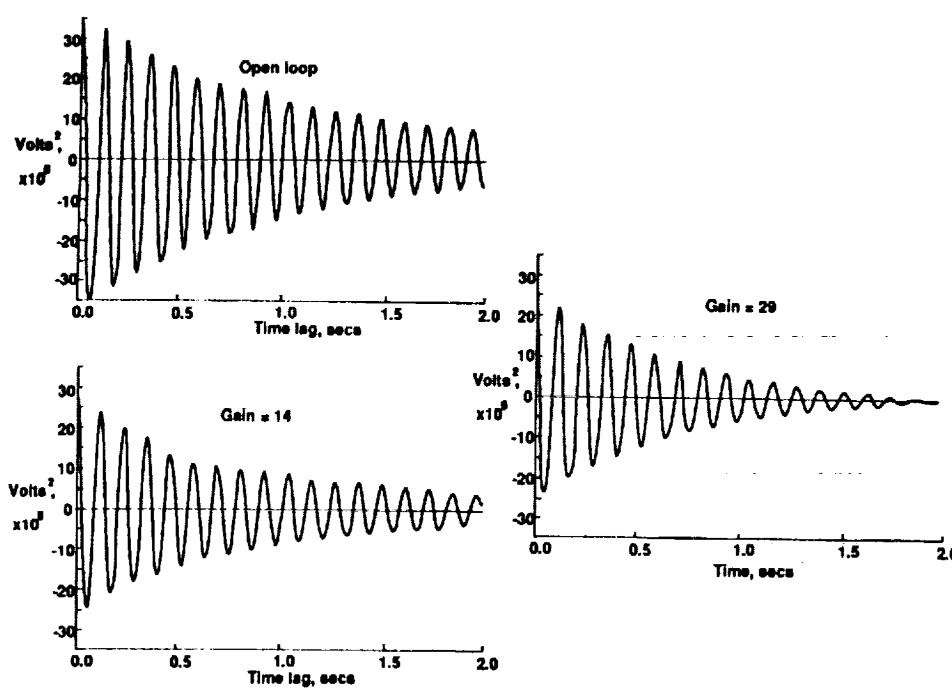


Figure 12. - Autocorrelation functions for a velocity of 19.4 knots.

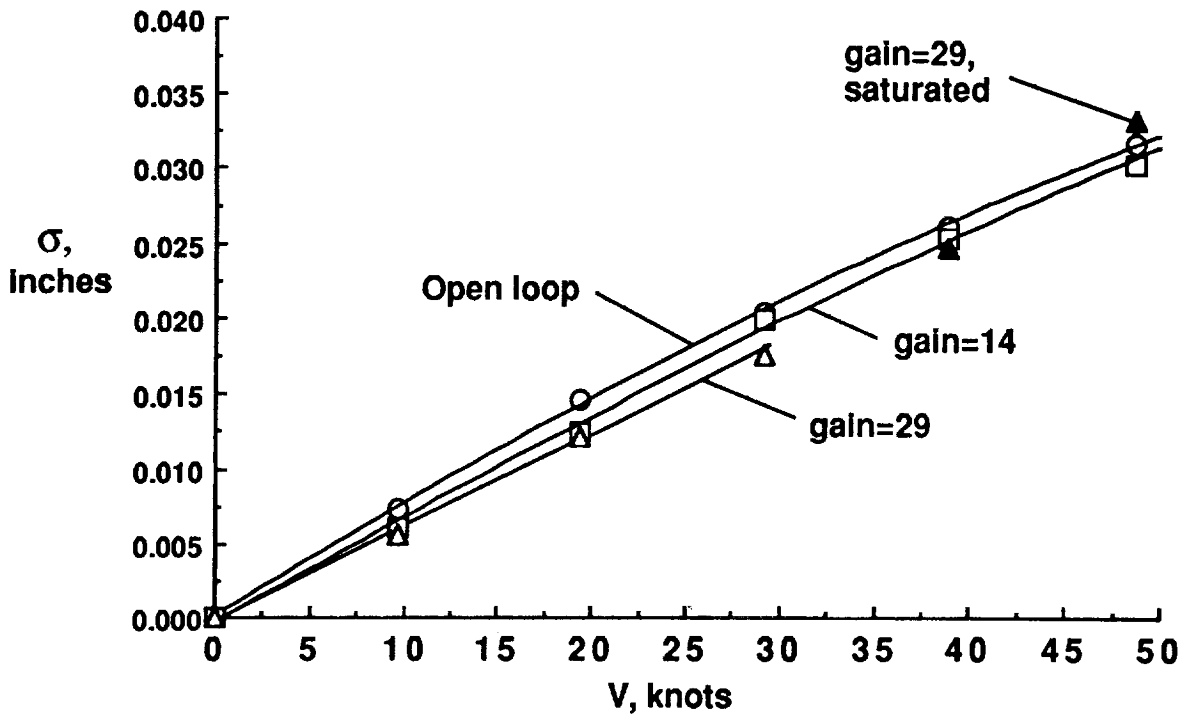


Figure 13. - Variation of root-mean-square response with velocity.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
February 1993

3. REPORT TYPE AND DATES COVERED
TECHNICAL MEMORANDUM

4. TITLE AND SUBTITLE
Attenuation of Empennage Buffet Response Through Active Control of Damping Using Piezoelectric Material

5. FUNDING NUMBERS
590-14-61-01

6. AUTHOR(S)
Jennifer Heeg, Jonathan M. Miller, and Robert V. Doggett, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-107736

11. SUPPLEMENTARY NOTES
Based on paper presented at Damping '93, San Francisco, CA, on February 24-26, 1993. Jonathan M. Miller is a student at Cornell University. He contributed to this work while he was on a cooperative education work assignment at NASA Langley.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited

Subject Category - 02

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Dynamic response and damping data obtained from buffet studies conducted in a low-speed wind tunnel by using a simple, rigid model attached to spring supports are presented. The two parallel leaf spring supports provided a means for the model to respond in a vertical translation mode, thus simulating response in an elastic first bending mode. Wake-induced buffeting flow was created by placing an airfoil upstream of the model so that the wake of the airfoil impinged on the model. Model response was sensed by a strain gage mounted on one of the springs. The output signal from the strain gage was fed back through a control law implemented on a desktop computer. The processed signals were used to "actuate" a piezoelectric bending actuator bonded to the other spring in such a way as to add damping as the model responded. The results of this "proof-of-concept" study show that the piezoelectric actuator was effective in attenuating the wake-induced buffet response over the range of parameters investigated.

14. SUBJECT TERMS
Aeroelasticity; buffeting; empennage; piezoelectric; active control

15. NUMBER OF PAGES
16

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18
298-102